The Araucaria Project. Population effects on the V and I band magnitudes of red clump stars

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ABSTRACT

We present measurements of the V and I band magnitudes of red clump stars in 15 nearby galaxies obtained from recently published homogenous HST photometry. Supplementing these results with similar data for another 8 galaxies available in the literature the populational effects on the V and I band magnitudes of red clump stars were investigated. Comparing red clump magnitudes with the I-band magnitude of the TRGB in a total sample of 23 galaxies possessing very different environments we demonstrate that population effects strongly affect both the V and I band magnitude of red clump stars in a complex way. Our empirical results basically confirm the theoretical results of Girardi and Salaris, and show that optical (VI) photometry of red clump stars is not an accurate method for the determination of distances to nearby galaxies at the present moment, as long as the population effects are not better calibrated, both empirically and theoretically. Near infrared photometry is a much better way to measure galaxy distances with red clump stars given its smaller sensitivity to population effects.

Subject headings: distance scale - galaxies: distances and redshifts

1. Introduction

The main goal of our long-term Araucaria Project (Gieren et al. 2005) is to substantially improve the extragalactic distance scale calibration with observations of several major distance indicators in a large sample of nearby galaxies possessing markedly different environments. Using high-quality optical and near-infrared photometry, and spectroscopic data collected for Cepheids, TRGB, RR Lyrae stars, blue supergiants, eclipsing binaries and red clump stars we are carefully addressing two of the most important sources of systematic error associated with the whole procedure of calibrating the cosmic distance scale: reddening, and the effect of population (metallicities and ages) on the various stellar distance indicators scrutinized in our program. In addition, this work is expected to produce a truly accurate (1 % total error) distance determination to the LMC which is the fiducial galaxy to which most measures of distances to other, more distant galaxies are currently tied.

The helium-burning stars of intermediate age called red clump stars are in principle a very attractive tool for distance determination, given their small ranges in absolute magnitude in any given photometric passband, their presence in most galaxies in large numbers which allows to determine the mean red clump magnitude typically to 0.01 mag or better, and the fact that red clump stars are very numerous also in the solar neighborhood. About 1000 red clump stars have trigonometric parallaxes measured with an accuracy better than 10 % by the Hipparcos satellite, which made it possible to calibrate the absolute magnitudes of the red clump with high accuracy (Paczynski and Stanek 1998, Alves 2000, Laney and Pietrzynski 2009).

The first measurements of the distance to the LMC based on the mean I-band magnitude of red clump stars led to a very short distance modulus of 18.23 mag (Udalski et al. 1998, Udalski 2000) and triggered a lively dispute in the astronomical community about the possible reality of a "short distance scale". Subsequent observations of red clump stars in clusters in the Magellanic Clouds indicated that the dependence of the mean I-band magnitude on age is practically negligible (within 0.05 mag) for the age range 2-8 Gyr (Udalski 1998). However, these results had to be taken with some caution given the fact that the studied LMC and SMC clusters had slightly different distances. Sarejedini (1999) using data of Galactic open clusters found that there are important

population effects on both V and I band magnitudes of red clump stars. Detailed studies of the dependence of I_{RC} on metallicity were performed on a large set of nearby red clump stars with accurate distances and spectroscopic metallicities (McWilliam 1990). Within the range of metallicities covered by these nearby red clump stars (-0.6 < [Fe/H] < +0.35; McWilliam 1990, Liu et al. 2007) the slope of the brightness-metallicity relation was found to be a rather modest 0.14 mag/dex (Udalski 2000, ApJ, 531, L25).

Important progress was made by Alves (2000) who took the work to the near-infrared domain and calibrated the K-band absolute magnitudes of a large sample of Hipparcos-observed nearby red clump stars. An outstanding and obvious advantage of using K-band data is that it practically eliminates any dependence of the obtained results on the adopted reddening. Alves (2000) was also able to show that the mean K-band magnitude of the red clump does not depend on metallicity in the range from -0.5 to 0.0 dex. The distance modulus measured to the LMC using the Alves calibration surprisingly and consistently turned out to be close to 18.50 mag (Alves et al. 2002, Pietrzynski and Gieren 2002), in conflict with the earlier result from the I-band magnitude of the red clump in the LMC. Girardi and Salaris (2001), and Salaris and Girardi (2002), assuming a star formation history and chemical evolution history, computed theoretical population corrections which must be applied to the optical and near-IR magnitudes of red clump stars in order to calculate correct distances to nearby galaxies. They argued that the observed discrepancy between the distances to the LMC measured from the red clump in I and K bands is a consequence of the larger population effect in the I band. Unfortunately, the corrections predicted by their models are very uncertain (about 0.1 mag) due to uncertain star formation and chemical evolution histories and shortcomings in the stellar models, making it imperative to improve the accuracy of these theoretical predictions, or providing an accurate empirical determination of the population effect in the different bands.

In the course of the Araucaria project we determined the mean near-IR magnitudes of the red clump in four Local Group galaxies (LMC, SMC, Carina and Fornax; Pietrzynski, Gieren and Udalski 2003). Comparison of the measured mean K-band magnitude to the magnitudes of other distance indicators (Cepheids, TRGB, RR Lyrae stars) showed, in very good agreement with the results of Alves (2000), and of van Helshoecht and Groenewegen (2007), that in this band the population effects on the brightness of the red clump are indeed very small. Again, the distance moduli based on the near-IR calibration of the red clump method to the four studied galaxies turned to be longer by almost exactly 0.21 mag when comparing to the corresponding distances obtained from the optical I-band photometry. Therefore the large discrepancy between the distances obtained in the optical and near-IR may be either explained by very significant population effects on the optical brightness of the red clump stars, or by a large zero point error in one of the calibrations.

Since in particular the calibration of Alves (2000) is based on very old photometry collected in 1960s, a significant zero point error in the calibration did not seem to be completely ruled out. In order to check on this possibility very recently a new, modern calibration of the K, H and J band magnitudes of red clump stars has been obtained (Laney and Pietrzynski 2009) which is based on observations of nearby Galactic red clump stars with the infrared photometer attached to the 0.75-m telescope at the SAAO observatory. With the new accurate calibration ($M^{K}_{RC} = -1.615 \pm 0.03$ mag) we measured a LMC distance of 18.47 $\pm$ 0.03 mag in near-perfect agreement with our our recent distance determination to this galaxy based on a late - type eclipsing binary (Pietrzynski et al. 2009) and near-infrared photometry of RR Lyrae stars (Szewczyk et al. 2009). All these results indicated that there are indeed large population effects on the optical magnitudes of red clump stars, as oppose to their near-infrared magnitudes, but a convincing empirical demonstration of this conjecture had yet to be made, and is the purpose of this paper where we take advantage of the recently published (Jacobs et al. 2009) uniform HST photometry of a significant number of nearby galaxies containing large numbers of red clump stars and stars populating the red giant branch.

2. Mean V and I band red clump magnitudes

The relatively faint absolute magnitudes of red clump stars seriously limited the number of nearby galaxies in which accurate mean V and I band magnitudes of the red clump were measured and analyzed so far (e.g. Udalski et al. 2000), preventing sound empirical conclusions about the population effects in these bands on the brightness of these stars. Very recently Jacobs et al. (2009) published a compilation of deep HST photometry of some 250 galaxies in the Local Volume. Taking advantage of this new and formidable database we decided to use this deep and uniform photometry to calculate accurate V and I band mean red clump magnitudes in 15 Local Group galaxies in which the HST photometry reaches at least two magnitudes below the faintest red clump stars, making a very precise measurement of the clump magnitude possible. We did this measurement applying fitting function (1), which consists of a Gaussian component representing the red clump stars and a second-order polynomial approximating the stellar background (RGB stars), to the data. Based on this procedure the mean V and I band magnitudes of the red clump were determined in each target galaxy with a typical accuracy of 0.01 mag (see Figure 1, and Table 1).

$$n(K) = a + b(K - K^{\max}) + c(K - K^{\max})^2 + \frac{N_{RC}}{\sigma_{\rm RC}\sqrt{2\pi}} \exp\left[-\frac{(K - K^{\max})^2}{2\sigma_{\rm RC}^2}\right] \qquad (1)$$

In order to determine a uniform set of metallicities for our target galaxies, we applied the calibration of the V-I color of the Red Giant Branch (RGB) versus metallicity relation of Da Costa and Armandroff (1990) to the same HST data. We note that this relation was derived from old globular clusters and might need a correction for galaxies having a significant population of younger RGB stars. In order to roughly estimate the expected change in the metallicity determination from the Da Costa and Armandroff relation for such systems (e.g. NGC 6822, IC 1613, M33, M31) we adopted several star formation histories and computed the expected corrections. These were found to be very small (about 0.1 dex) which is likely within the systematic uncertainties of the metallicities derived from the Da Costa and Armandroff relation. Therefore we decided not to apply them to the calculated metallicities.. The results are presented in Table 1, together with the values of the I-band magnitude of the TRGB measured from the same data by Rizzi et al. (2008). Foreground reddenings estimated from the reddening maps of Schlegel et al. (1999) are also given.

3. Comparison with the I band of TRGB

In this section we will determine the differences between the mean I-band magnitudes of the red clump and the corresponding I-band magnitudes of the TRGB in our sample of galaxies, and relate these magnitude differences to the metallicities in Table 1. For several reasons such a differential comparison provides a very strong test on populational effects on the brightness of the red clump. Indeed, many nearby galaxies possess large populations of RGB and red clump stars, so the corresponding brightness of these two distance indicators can be measured with very good accuracy. Moreover, reasonably assuming that both red clump star and TRGB magnitudes are affected by interstellar extinction in the same way, the differential I-band magnitudes will be free of problems related to the reddening, and potential errors of the photometric zero points. Using the data presented in Table 1 together with the corresponding information for 8 additional galaxies tabulated by Udalski (2000), we calculated the $\mathrm{I_{TRGB} - I_{RC}}$ for 23 nearby galaxies and plotted these differences versus the corresponding metallicities in Fig. 2. Since it is widely accepted now that the absolute I-band magnitude of the TRGB depends only very weakly on metalliciy and age (e.g. some 0.04 mag/dex, Rizzi et al. 2007) the scatter on Fig. 2 must be mostly related to the populational dependence of the mean I-band magnitude of the red clump stars.

4. Discussion

Several features which are seen on Fig. 2 deserve to be commented. First of all, a scatter among the data points up to 0.4 mag is present, which fully confirms the results obtained from the theoretical models of Girardi and Salaris (1999) that there is a very significant population effect on the I-band magnitude of red clump stars. Fig. 2 shows this fact for the first time empirically, in a very clear fashion. Furthermore, a trend is present in the sense that the red clump in I becomes fainter with respect to the TRGB in I as the stellar metallicity increases.

The mean I-band magnitude of red clump stars calculated from a mixture of different populations can in principle depend on metallicity in a very complicated way through the star formation and chemical evolution histories. The simple linear relation in Fig. 2 was plotted to demonstrate that a strong population effect is present, rather than with the intention to properly quantifying it. Even, in such a simple plot a general dependence of $\mathrm{I}^{\mathrm{TRGB}} - \mathrm{I}^{\mathrm{RC}}$ on metallicity of the order of 0.21 mag/dex is seen. This is in good agreement with the metallicity dependence of the I-band magnitude of the red clump found by Udalski (2000) and Pietrzynski, Gieren and Udalski (2003). However, the large scatter of the data points around a simple linear relation indicates that other factors (e.g. dependence on age, a more complicated non-linear dependence on metallicity) likely play an important role.

It is also worthwhile to mention that, as can be seen from Fig 2, selecting different subsamples of galaxies and plotting $\mathrm{I}^{\mathrm{TRGB}} - \mathrm{I}^{\mathrm{RC}}$ versus metallicity one can easily obtain very different conclusions about the populational effect on the I-band magnitude of red clump stars, from no dependence at all on metallicity to a very strong dependence. In particular the $\mathrm{I}^{\mathrm{TRGB}} - \mathrm{I}^{\mathrm{RC}}$ is close to 3.6 mag (with a scatter of about 0.1 mag) for all galaxies having a mean metallicity larger than about -1.9 dex (except DDO 74). In more metal-poor galaxies, the absolute I magnitude of the red clump seems to become brighter by 0.4 mag when going from -1.9 to -2.4 dex. As said before, the current data in Fig. 2 do suggest a non-linear relationship between the difference of red clump and TRGB absolute magnitudes in the I band, and the metallicity of these populations.

An analysis of the population effects on the V band magnitude of red clump stars can also be done from our data. However in order to compare the V^{RC}, with the $\mathrm{I}^{\mathrm{TRGB}}$ in a given galaxy we need to adopt a reddening for all studied galaxies and correct the corresponding magnitudes, which evidently complicates the analysis. Adopting the reddenings calculated from the maps of Schlegel et al. (1999) and assuming the reddening law given in the same paper we calculated the $\mathrm{V}_0^{\mathrm{RC}} - \mathrm{I}_0^{\mathrm{TRGB}}$ and plotted it against the metallicity in Figure 3. The diagram is very similar to Fig. 2, and again the large observed scatter among the data points indicates the presence of very significant population effects on the V band

magnitudes of red clump stars. The total variation of the difference between the red clump V-band magnitude and the I-band magnitude of the TRGB over the metallicity range covered by the present target galaxies appears even larger than in Fig. 2, suggesting an even stronger population effect on the V absolute magnitudes of red clump stars than in I, which is supported by the model predictions of Salaris and Girardi.

5. Summary and conclusions

Using deep and homogeneous HST photometry we have calculated precise mean I and V band magnitudes of the red clump, and have determined the intermediate-population mean metallicities for some 15 Local Group galaxies. Supplementing these results with data from the literature for another 8 galaxies we have compared the mean I- and V-band red clump magnitudes with the corresponding TRGB I-band magnitudes. Our analysis clearly shows that there are very significant population effects on both V and I band magnitudes of red clump stars, which fully confirm the results of Girardi and Salaris (2001) obtained from synthetic populations of red clump stars. Therefore, in order to use optical photometry of these stars for distance determinations to nearby galaxies the population effects should be very carefully addressed. Since there is at present no way to accurately determine such population effects empirically, the only possibility for measuring distances from this method is to assume star formation and chemical evolution histories in a given galaxy and to calculate, as originally proposed by Girardi and Salaris (1999), population corrections for a given band. Unfortunately, due to many assumptions (star formation history, chemical evolution history, stellar models) the accuracy of such corrections (about 0.1 mag) strongly limits the application of optical photometry of red clump stars for a precise determination of local distances. Luckily, as discussed previously in this paper, the situation is much better with using near-infrared photometry of red clump stars which allow a much more accurate distance determination to galaxies due to the decreased effect of population differences on the red clump absolute magnitude. This tendency is of course also supported by the decreased effect of reddening on the measured mean magnitude, particularly in the K band.

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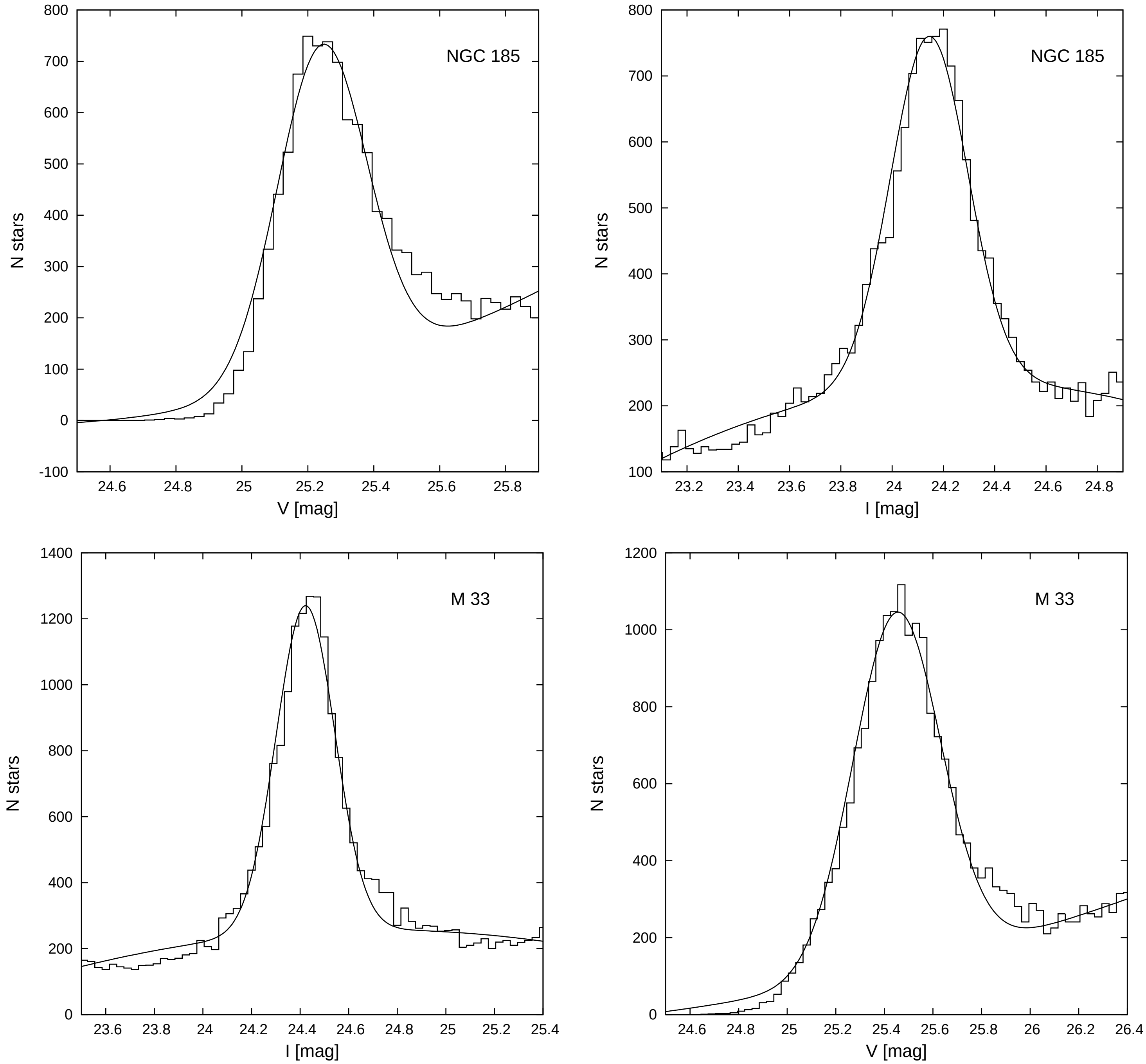

Fig. 1.— Exemplary Gaussian and polynomial fits, according to equation (1) to the HST data for nearby galaxies (Jacobs et al. 2009). The excellent accuracy of the determination of the mean V and I band magnitudes of red clump stars from these data is demonstrated.

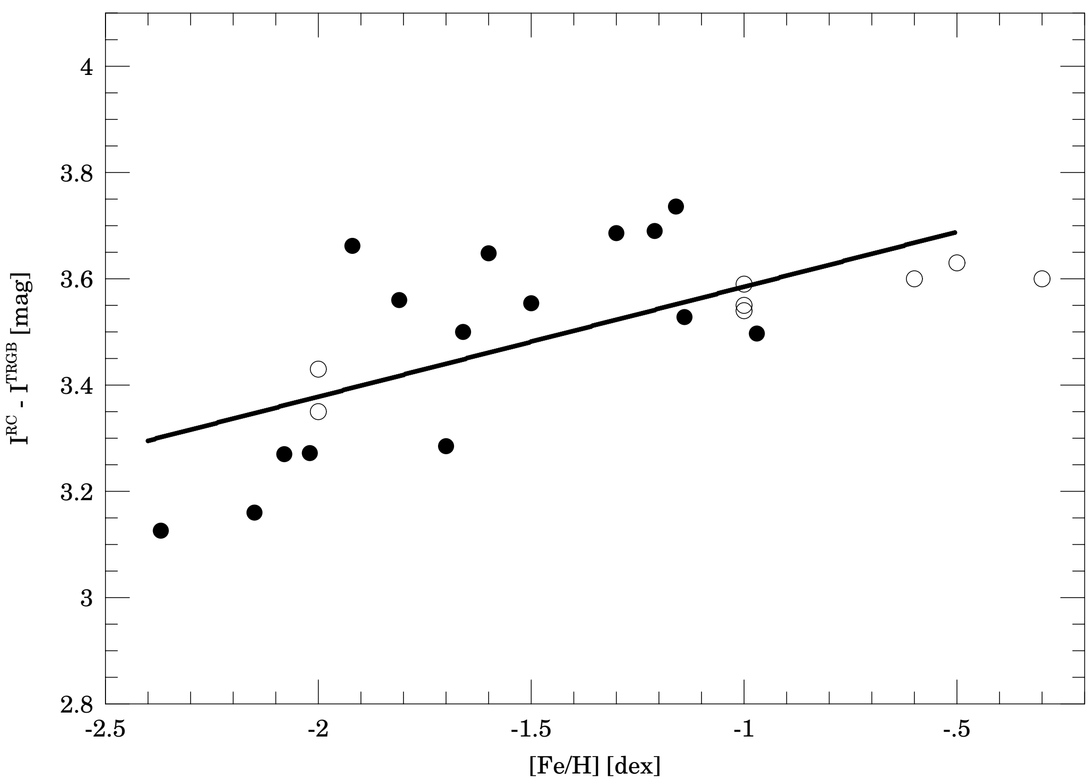

Fig. 2.— The difference between the mean I-band magnitude of red clump stars and the I-band TRGB brightness plotted against the mean metallicity for these stars, for 23 nearby galaxies. Filled and open circles correspond to the data obtained in this paper from recently published homegenous HST photometry, and data tabulated by Udalski et al. (2000), respectively. Error bars to the magnitudes (not shown in the Figure) are of the order of 0.05 mag.

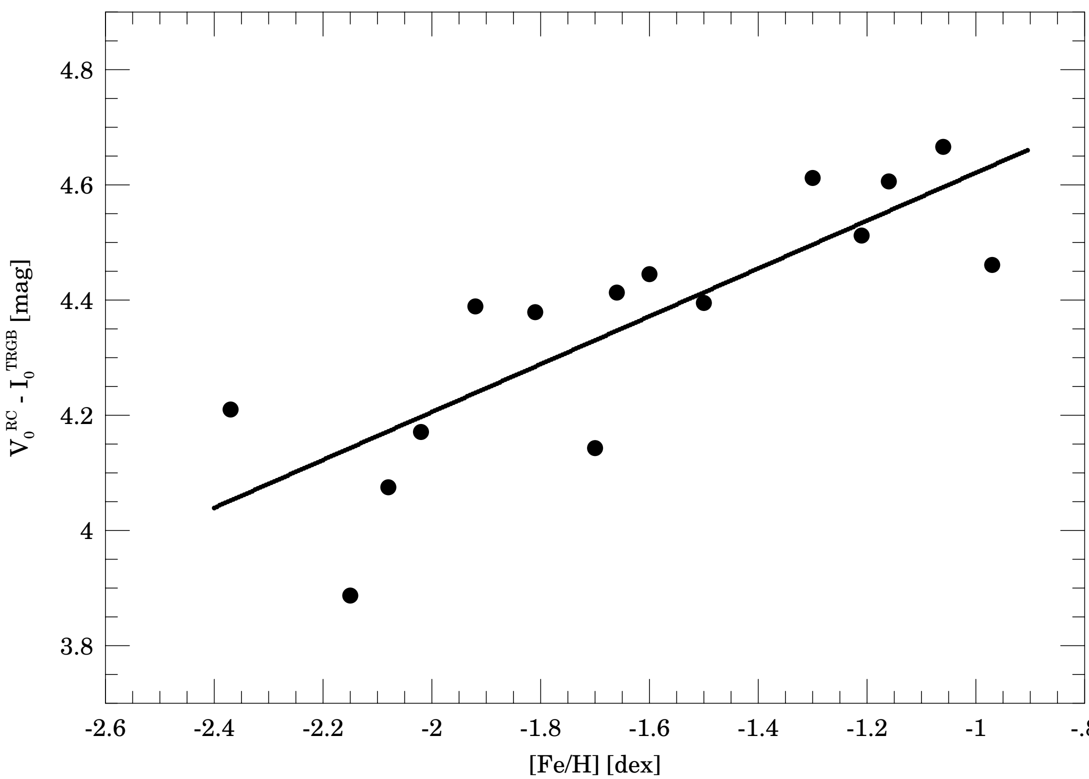

Fig. 3.— The difference between the mean, absorption-corrected V-band magnitude of red clump stars and the absorption-corrected I-band magnitude of the TRGB plotted against the metallicity of the stars, for 15 nearby galaxies. HST data were used for the determination of the magnitudes. Error bars to the magnitudes (not shown in the Figure) are of the order of 0.05 mag.

Table 1. Red clump and TRGB magnitudes, and metallicities calculated from homogenous HST data for 15 galaxies

Galaxy	I_{RC}	σ_I	V_{RC}	σ_V	I_{TRGB}	[Fe/H]	$\sigma_{[Fe/H]}$	E(B-V)
NGC6822	23.478	0.004	24.907	0.004	19.950	-1.06	0.03	0.23
IC1613	23.924	0.007	24.797	0.005	20.370	-1.50	0.02	0.03
DDO74	21.375	0.010	22.279	0.006	18.090	-1.70	0.06	0.04
Phoenix	22.660	0.024	23.593	0.010	19.160	-1.66	0.04	0.02
NGC185	24.136	0.003	25.238	0.004	20.400	-1.16	0.03	0.18
NGC147	24.360	0.003	25.403	0.002	20.670	-1.21	0.03	0.17
DDO69	24.002	0.015	24.927	0.007	20.730	-2.02	0.08	0.02
Pegasus	24.676	0.006	25.688	0.005	20.990	-1.30	0.03	0.07
DDO75	24.940	0.008	25.722	0.011	21.780	-2.15	0.04	0.04
M33	24.417	0.003	25.446	0.003	20.920	-0.97	0.03	0.05
E594-004	24.436	0.013	25.680	0.016	21.310	-2.37	0.06	0.12
Antlia	25.382	0.007	26.210	0.010	21.720	-1.92	0.01	0.08
E410-005	25.940	0.007	26.777	0.005	22.380	-1.81	0.02	0.01
UGC9128	26.020	0.009	26.854	0.010	22.750	-2.08	0.03	0.02
E294-010	26.118	0.013	26.923	0.010	22.470	-1.60	0.02	0.01